

Co-gasification of woody biomass and microalgae in a fluidized bed



Kai-Cheng Yang^a, Keng-Tung Wu^{a,*}, Ming-Huan Hsieh^a, Hung-Te Hsu^a,
Chih-Shen Chen^b, Hsiao-Wei Chen^b

^a Department of Forestry, National Chung Hsing University, Taichung 40227, Taiwan, ROC

^b Chemistry and Environment Research Laboratory, Taiwan Power Research Institute, New Taipei City 23847, Taiwan, ROC

ARTICLE INFO

Article history:

Received 17 January 2013

Received in revised form 13 June 2013

Accepted 21 June 2013

Available online 13 August 2013

Keywords:

Co-gasification

Fluidized bed

Torrefaction

Microalgae

Woody biomass

ABSTRACT

In this study, the microalgal (*Spirulina platensis*) torrefied pellet and woody biomass (*Eucalyptus globulus*) torrefied pellet were co-gasified in a 30 kW bubbling fluidized bed gasifier to investigate the effect of gasification temperature, equivalence ratio (ER), feedstock mixing ratio and steam injection on syngas compositions, the lower heating value (LHV), tar content, etc. Before feeding into the gasifier, the microalgal and woody biomass pellets were torrefied to increase the heating values.

It can be found that the ash content of microalgal torrefied pellet is much higher than that of woody biomass torrefied pellet. Although ash compositions can act as catalysts to enhance the gasification reaction, the extreme higher amount of ash may cause sintering and agglomeration during gasification. From the above co-gasification experiments, the results show that CO and CO₂ contents increase with increasing the ER, and CH₄ and H₂ show the contrary tendency. Increasing the mixing ratio of the microalgal torrefied pellet, H₂, and CH₄ contents first decrease and then increase slightly, but CO and LHV first increase and then decrease. Injecting steam can increase H₂ and CO₂ yields, but decrease CH₄ and CO yields, and LHV. It can be found that the high-content ash in the microalgal torrefied pellet dominates the gasification products, and the results show the contrary tendency compared with gasification of woody biomass torrefied pellet.

© 2013 Taiwan Institute of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

1. Introduction

Currently more than 95% of energy in Taiwan relies on import [1]. In order to mitigate the impact of energy import, reducing the dependence on the fossil fuel is an important task. The Government has already stipulated the certain renewable energy development goal, in which the biomass energy is the most important renewable power utilization beside conventional hydropower in Taiwan [1]. Now to accelerate the large utilization of biomass energy in Taiwan, gasification then is considered as a technology to recover energy from biomass.

Gasification can be defined as the conversion of carbonaceous feedstock, e.g. waste, by partial oxidation at the elevated temperature [2]. Recently Long and Wang [3] investigated co-gasification of coal and biomass to understand the effect of increasing biomass feeding ratio on operation of an IGCC plant, and recommended that the co-gasification process is more effective than a single gasification operation. The successful experience of the Lahden Lämpövoima Oy's Kymijärvi power plant gasification project has also demonstrated that the direct gasification of biomass in a commercial atmospheric CFB gasifier developed by

the Foster Wheeler Energia Oy, Finland [4]. Also, it has been proven that co-gasification of different fuels is feasible [5–7].

On the other hand, microalgae have long been recognized as potential biomass resource for energy production [8]. Taiwan Power Research Institute (TPRI) is working on the growth of microalgae by using flue gas from coal power plants to fix carbon dioxide. However, crumbled microalgae must be pre-treated by pelletization and torrefaction to improve the fuel quality before utilization as fuels. After torrefaction, the fuel quality of torrefied microalgae is close to the coal [9].

Thus, the objective of this investigation is to expand the utilization of microalgae as fuels. All experiments were carried out in a 30 kW bubbling fluidized bed gasifier to investigate co-gasification of the microalgal torrefied pellet and woody biomass torrefied pellet. The effects of gasification temperature, equivalence ratio (ER), feedstock mixing ratio and steam injection on syngas compositions, the lower heating value (LHV), and tar content were analyzed to understand the feasibility of employing microalgae as the gasification feedstock.

2. Experimental

The experiments were carried out in a 30 kW bubbling fluidized bed gasification system including the gasification chamber with a

* Corresponding author. Tel.: +886 4 22840345x140; fax: +886 4 22873628.
E-mail address: wukt@nchu.edu.tw (K.-T. Wu).

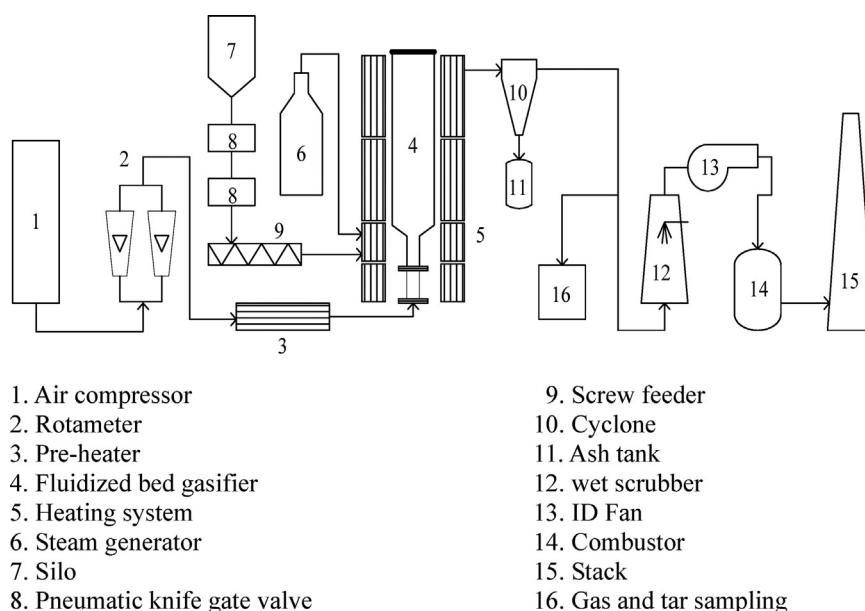


Fig. 1. Flow diagram of the fluidized bed gasification system.

windbox, the feeding system, the air supply system, and the syngas treatment section. Fig. 1 shows the flow diagram of the bubbling fluidized bed gasifier employed in this study. The gasification chamber, with a diameter of 7.6 cm in the bed region, 19.8 cm in the freeboard region, and a total high of 1.9 m, was constructed of 6 mm SUS310 stainless steel covered with ceramic fiber to limit heat loss. A cylindrical windbox with a conical bottom, 30 cm in height and 7.6 cm in diameter, connected to the air supplied line was fabricated of 6 mm stainless steel. The air pre-heated by an electric heater was served as the fluidization gas through a perforated plate distributor of 2 mm stainless steel with an open area ratio of 2%. The gasification chamber is kept at the operating temperature by means of the electric heating system covered the bed region. The feeding of the feedstock into the gasifier at the position above the sand bed was carried out continuously. The two-stage feeding system includes a hopper with two pneumatic knife gate valves to block air, and a screw feeder is connected to the gasifier.

The syngas leaving the gasifier entered a cyclone for the primary cleaning. Ash and unburned char dropped from the cyclone into a sealed vessel for removal. A tar measurement system [10] was installed after the exit of the cyclone for tar sampling and analysis. The syngas was sampled at the location of the tar measurement system. The components of the syngas, such as CO, CO₂, H₂, and CH₄ were analyzed by employing an Agilent 7890A gas chromatograph (off-line) during the steady state operation. The

syngas exited from the cyclone and passed to a wet scrubber, then was discharged via the stack after a combustor.

The microalgal torrefied pellet and woody biomass torrefied pellet with a diameter of 6 mm, and a length of 10 mm were used as feeding fuels. The microalgae, *Spirulina platensis*, were supplied by Taiwan Power Research Institute, and the woody biomass, *Eucalyptus globulus*, was bought from Cheng Hsing Industry Co. in Nantou County. The feedstock was firstly pelletized by a flat die pellet mill. Afterwards, the pellet was torrefied at 250 °C for 1 h. The proximate and ultimate analyses of fuels are listed in Table 1. Silica sand was employed as the bed material in this study and the mean size of the sand was 0.437 mm in diameter with a minimum fluidization velocity of 18.9 cm/s.

3. Results and discussion

3.1. Gasification of woody biomass torrefied pellet and microalgal torrefied pellet

The air equivalence ratio (ER) is defined as the ratio of the desired air flow rate to the stoichiometric air flow rate for complete combustion. Fig. 2 shows the effect of the ER on syngas composition from gasification of woody biomass torrefied pellet and microalgal torrefied pellet at 800 °C, respectively. From Fig. 2(a), it can be found that the yields of syngas, H₂, CO, and CH₄ decrease with increasing the ER respectively, but that of CO₂ increases with increasing the ER. Because the higher ER value represents injecting more oxygen into the gasifier, the oxidation (combustion) reaction ($C + O_2 \rightarrow CO_2$) enhances the CO₂ production according to Le Chatelier's principle [11]. The results are also in agreement with the work of Narváez *et al.* [12] and Qin *et al.* [13].

Comparing Fig. 2(b) with (a), gasification of microalgal torrefied pellet shows the contrary tendency. It may be attributed to the extreme higher ash content in the microalgae. It can be seen in Table 1 that the ash content of the microalgal torrefied pellet is 9.00%, much higher than that of most woody biomass. Most ash compositions in biomass are alkali metals, and they can act as catalysts to enhance the gasification reaction. However, the extreme higher amount of ash may cause sintering and agglomeration during gasification, and it is unfavorable to produce syngas. Conducted by inductive coupled plasma emission spectrometer (ICP), we found that the potassium content is 15,454 mg/kg and

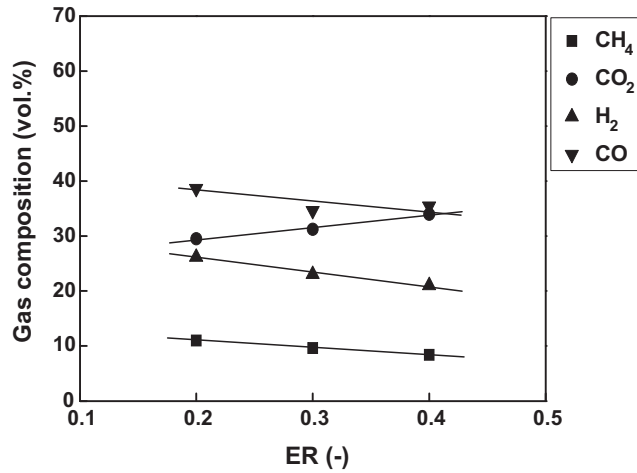
Table 1
Characteristic analyses of fuels.

Feedstock	Microalgae		Woody biomass	
Species	<i>Spirulina platensis</i>		<i>Eucalyptus globulus</i>	
Type	Pellet	Torrefied pellet	Pellet	Torrefied pellet
Ultimate analysis (wt%, dry)				
C	47.83	48.94	44.96	48.02
H	7.37	6.76	5.33	5.66
N	10.87	10.64	0.64	0.28
S	0.66	0.72	0.42	0.23
O	25.58	23.94	43.99	43.19
Proximate analysis (wt%, a.r.)				
Moisture	11.81	2.21	13.34	5.66
Ash	7.69	9.00	4.66	2.62
Combustible	80.50	88.79	82.00	91.72
Heating value (MJ/kg, a.r.)				
HHV ^a	19.67	22.33	16.49	19.62

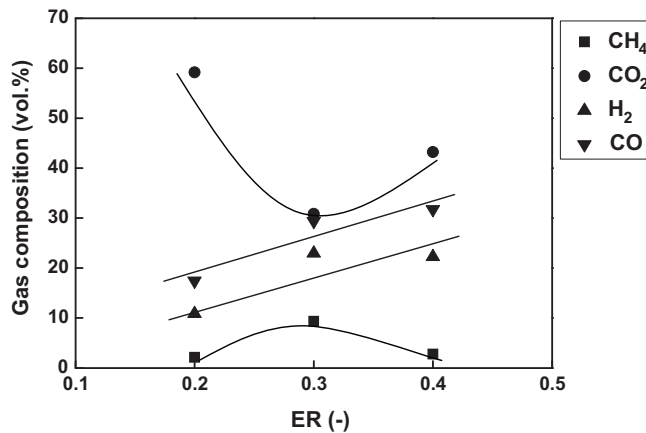
^a HHV, higher heating value.

sodium content is 3448 mg/kg in the microalgal torrefied pellet. Fig. 3 shows the picture of the sintering and agglomeration products of microalgal torrefied pellets and bed materials in the gasification process. The larger agglomeration may also lead to the

defluidization phenomenon during gasification. In Fig. 2, it can also be seen that gasification of the microalgal torrefied pellet produced higher CO_2 content at the same gasification condition. Therefore, more investigations may need to conduct to understand the role of the high-content ash in microalgae during gasification.



(a) Woody biomass pellet



(b) Microalgal torrefied torrefied pellet

Fig. 2. Effect of ER on syngas composition from gasification of fuels (gasification temperature = 800 °C). (a) Microalgal torrefied pellet; (b) woody biomass torrefied pellet.

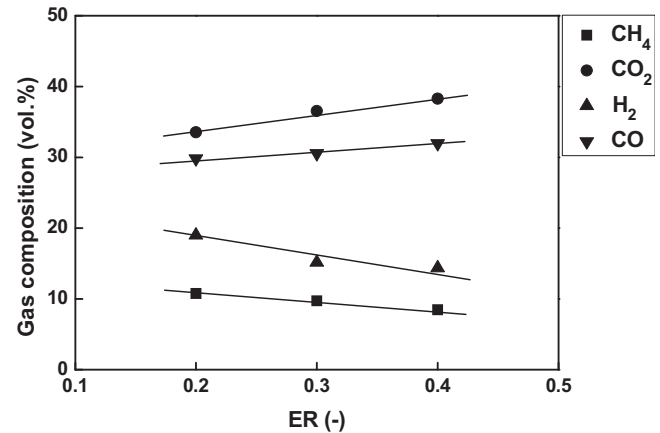


Fig. 3. Agglomeration of fuels and bed materials.

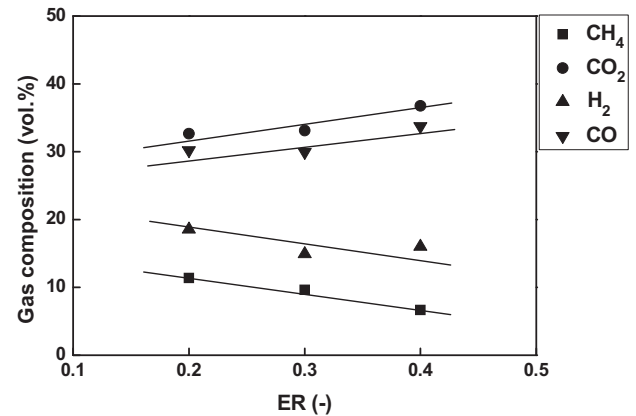
3.2. Co-gasification of woody biomass torrefied pellet and microalgal torrefied pellet

3.2.1. Effect of ER and gasification temperature

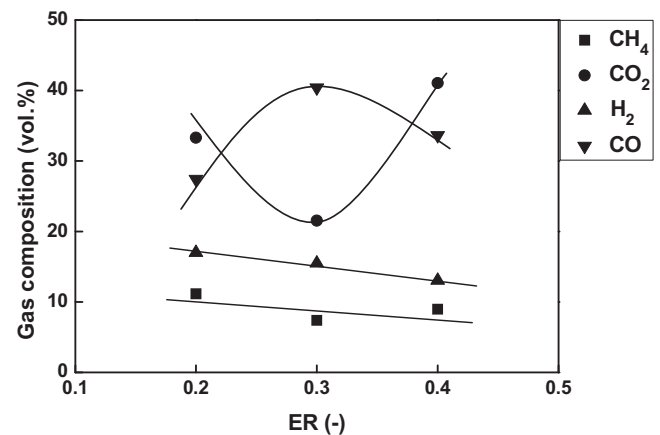
The woody biomass torrefied pellet and microalgal torrefied pellet were mixed for co-gasification. The mixing ratios of the



(a) Mixing ratio of microalgal torrefied pellet = 20%



(b) Mixing ratio of microalgal torrefied pellet = 30%



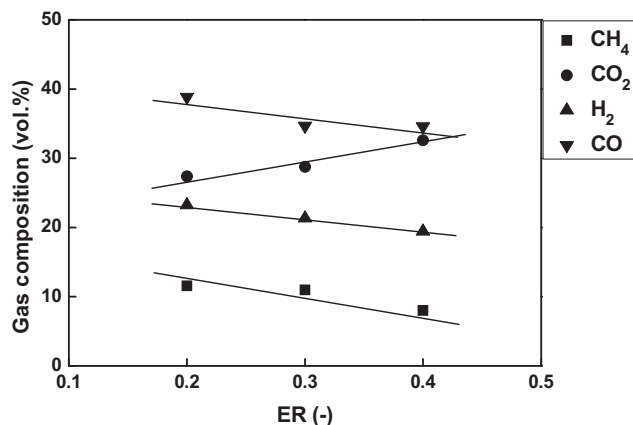
(c) Mixing ratio of microalgal torrefied pellet = 50%

Fig. 4. Effect of ER on syngas composition from co-gasification at 700 °C.

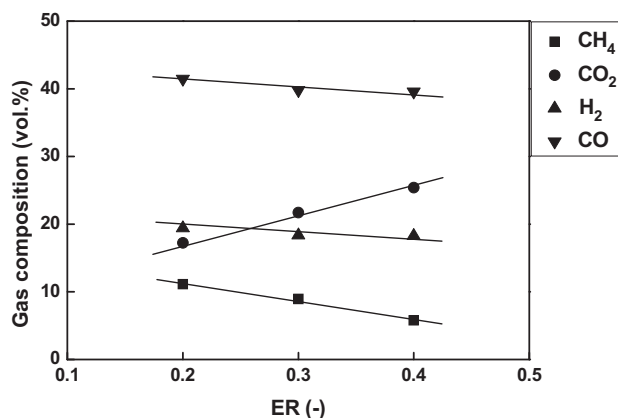
microalgal torrefied pellet were 20 wt%, 30 wt%, and 50 wt%. Fig. 4 shows the effect of ER on the syngas composition from co-gasification at 700 °C. In Fig. 4(a and b), it can be found that the same tendency of varied syngas composition at different mixing ratios. CO and CO₂ contents increases with increasing the ER, and CH₄ and H₂ show the contrary tendency. In addition, CO₂ content is always higher than CO. It is the similar reason described above that the higher ER value represents injecting more oxygen into the gasifier, so the oxidation (combustion) reaction enhances the CO₂ production. However, CO and CO₂ contents in Fig. 4(c) show the

different results. CO first increases then decreases, and CO₂ shows the contrary tendency. It is suggested that increasing mixing ratio of the microalgal torrefied pellet at lower gasification temperature may affect the syngas production due to higher ash content. As we mentioned above, more investigations may need to conduct.

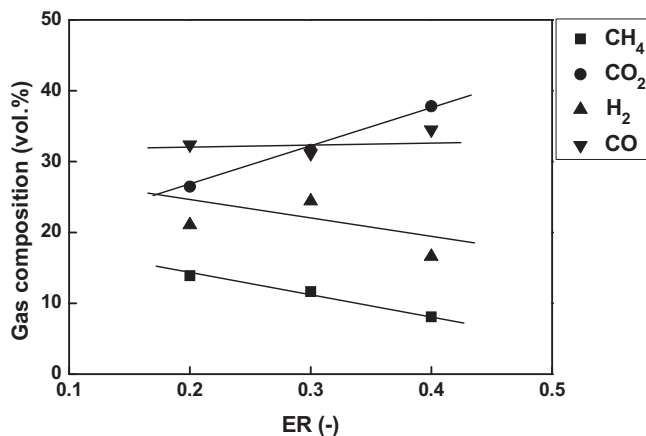
Fig. 5 shows the effect of ER on the syngas composition from co-gasification at 800 °C. The similar tendency of varied syngas composition at different mixing ratios is also found in Fig. 5(a–c), but the CO₂ content is lower than CO, compared with Fig. 4. It is attributed to the endothermic water gas reaction ($C + H_2O \rightarrow CO + H_2$) and Boudouard reaction ($C + CO_2 \rightarrow 2CO$) occurred at above 800 °C [14].



(a) Mixing ratio of microalgal torrefied pellet = 20%

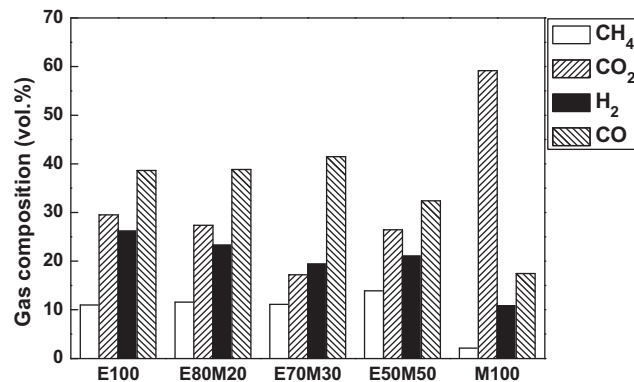


(b) Mixing ratio of microalgal torrefied pellet = 30%

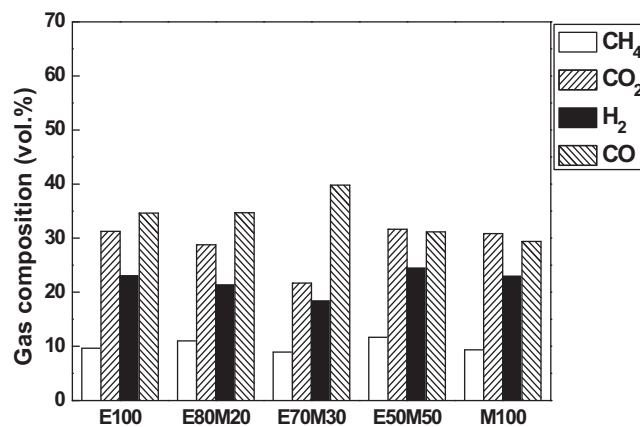


(c) Mixing ratio of microalgal torrefied pellet = 50%

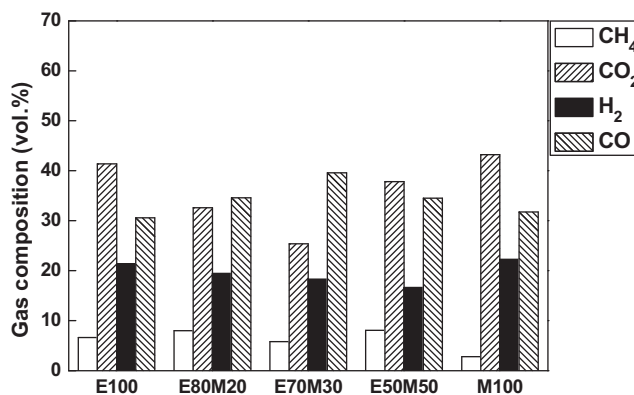
Fig. 5. Effect of ER on syngas composition from co-gasification at 800 °C.



(a) ER = 0.2



(b) ER = 0.3



(c) ER = 0.4

Fig. 6. Effect of mixing ratio of microalgal torrefied pellet on syngas composition from co-gasification at 800 °C.

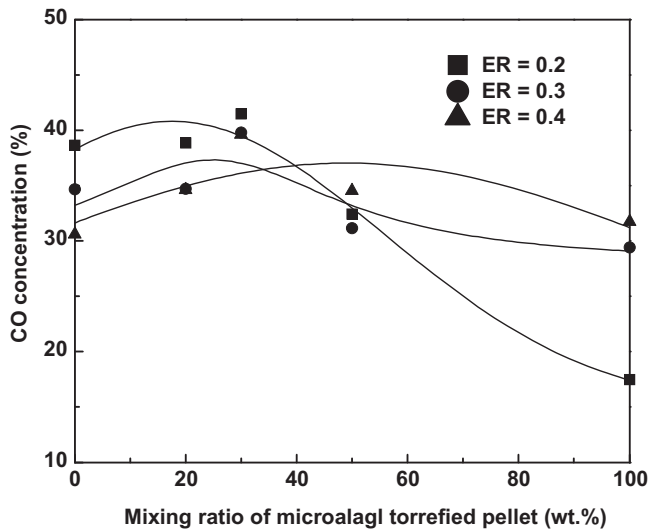


Fig. 7. Effect of mixing ratio of microalgal torrefied pellet on CO yield (gasification temperature = 800 °C).

3.2.2. Effect of mixing ratio

Fig. 6 shows the effect of mixing ratio on syngas composition for co-gasification at 800 °C with different ER. The codes shown in figures are represented as mixing ratio of woody biomass torrefied pellet and microalgal torrefied pellet. For example, E80M20 stands 20% of the microalgal torrefied pellet (M) mixed with 80% of the woody biomass torrefied pellet (E), and M100 means that the feeding fuel is the microalgal torrefied pellet (M) only. The other codes follow the same rules.

From Fig. 6(a–c), it can be seen that H₂ and CH₄ first decrease and then increase slightly with increasing the mixing ratio of the microalgal torrefied pellet (M). On the other hand, CO first increases and then decreases, while CO₂ shows the contrary results. Therefore, adding the proper amount of microalgal torrefied pellets can enhance CO yield. However, while mixing ratio of the microalgal torrefied pellet is up to 50%, the CO production decreases, shown in Fig. 7. It is suggested that the decrease of CO is caused by sintering of the microalgal torrefied pellet described in Section 3.1. From Fig. 7, the largest amount of CO product always can be found while the mixing ratio of the microalgal torrefied pellet is 30% (E70M30). After adding more microalgal torrefied pellet, the CO yield decreases. It can also be found that the maximum product of CO is 41.48% at ER = 0.2.

3.2.3. Heating value of syngas

The lower heating value (LHV), known as net calorific value, is calculated by subtracting the heat of vaporization of the water from the higher heating value (HHV). Usually LHV is used for practical cases, and it represents an indicator of syngas quality. The LHV of syngas can be calculated by following equation [15]:

$$\text{LHV (MJ/N m}^3\text{)} = \frac{(30 \cdot [\text{CO}] + 25.7 \cdot [\text{H}_2] + 85.4 \cdot [\text{CH}_4] + 151.3 \cdot [\text{C}_n\text{H}_m]) \cdot 4.2}{1000} \quad (1)$$

The units of gas compositions in the square brackets are wt%. Fig. 8 shows the effect of mixing ratio of the microalgal torrefied pellet on the lower heating value of syngas with different ER at 800 °C. The tendency is similar to Fig. 7, i.e., LHV first increases and then decreases with increasing the mixing ratio of the microalgal torrefied pellet. Therefore, the CO concentration dominated the LHV. Also, the maximum LHV occurs at feeding 30% of the microalgal torrefied pellet.

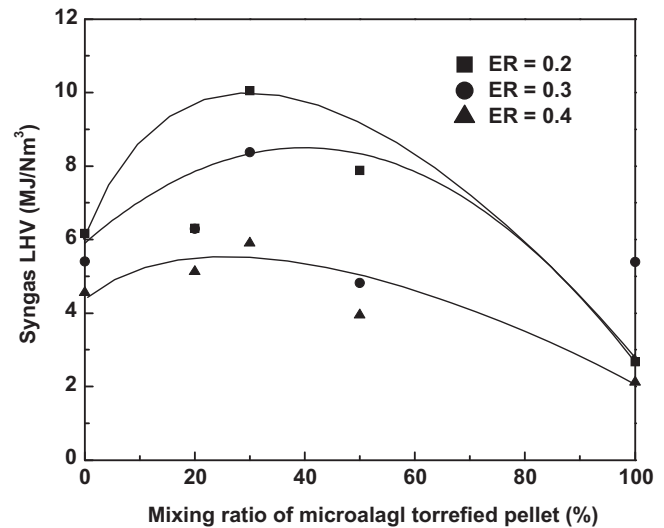


Fig. 8. Effect of mixing ratio of microalgal torrefied pellet on syngas LHV (gasification temperature = 800 °C).

3.2.4. Effect of steam injection

In order to understand the effect of the steam injection on syngas and LHV, the gasification test was carried out with injecting 0.86 kg/h of 128 °C steam at ER = 0.3. Fig. 9 shows injecting steam increase H₂ and CO₂ yields, but decrease CH₄ and CO yields. It is attributed to that injecting steam enhances char decomposition ($\text{C} + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 2\text{H}_2$), water–gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$), and methane reforming reaction ($\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2$) [16], especially at 700 °C. The occurrence of the water gas reaction ($\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2$) is not obvious at 800 °C, because injecting steam will decrease the bed temperature. On the other hand, it also can be seen that the water–gas shift reaction dominated the gasification process at lower temperature, so a large amount of CO₂ increases after injecting steam.

The effect of injecting steam on LHV is shown in Fig. 10. It can be found that injecting steam decreased the LHV. As mentioned above, it is attributed to that a large amount of CO₂ increases after injecting steam. Also, injecting steam enhances the risk of agglomeration of the feedstock and bed materials. It would affect the yield of syngas.

3.2.5. Tar contents

Tar can be defined as all organic compounds in biomass-derived syngas with a molecular weight larger than benzene [10]. The

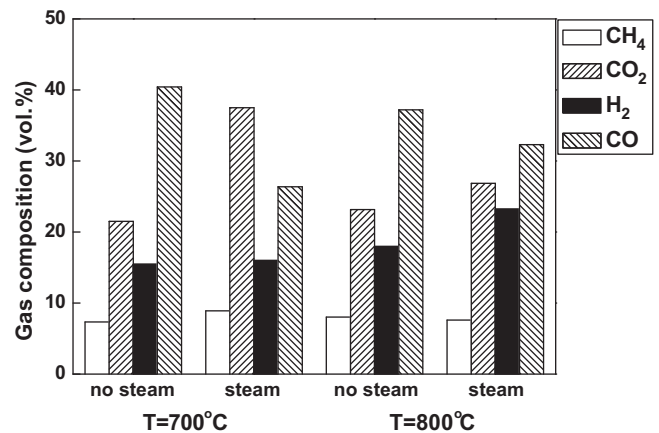


Fig. 9. Effect of steam injection on syngas composition (ER = 0.3, mixing ratio of microalgal torrefied pellet = 50%).

Table 2

Effect of operational conditions on syngas composition, syngas LHV and tar content.

Operational condition	Temperature ↗	ER ↗	Mixing ratio of microalgal torrefied pellet ↗	Steam injection
CO	↗	↘	↗↘	↗
CO ₂	↘	↘	↗↘	↘
CH ₄	↘	↘	↗↘	↘
H ₂	↗	↗	↗↘	↗
LHV	↗	↗	↗↘	↗
Tar	↘	↘	↗↘	↗

effect of steam injection on tar content is shown in Fig. 11. From Fig. 11, it can be found that the steam injection can reduce tar content at the lower mixing ratio of the microalgal torrefied pellet. It is implied that a small amount of ash mixed with steam enhances tar removal. However, if agglomeration occurs caused by ash compositions mixed with steam, the tar content would increase. The results caused by agglomeration can be found at E50M50 in Fig. 11.

3.3. Summary of effect of operational conditions on syngas characteristic

Table 2 summarized the effect of operational conditions (temperature, ER, mixing ratio of microalgal torrefied pellet, and steam injection) on syngas compositions, LHV, and tar content. The upward or downward arrows in Table 2 represent increasing or decreasing the level of operational conditions. The variations of the

gasification products by manipulating the operational conditions can be found in the table. Therefore, we can find the product we want by combining the different operational conditions. Generally speaking, co-gasification of microalgal torrefied pellet with the woody biomass pellet is feasible. As a result, reducing the feeding amount of microalgal pellet (<30%) in the gasification process could reduce the risk of agglomeration in the fluidized bed.

4. Conclusions

The microalgal torrefied pellet and woody biomass torrefied pellet have been co-gasified in a 30 kW bubbling fluidized bed gasification system to investigate the effects of various operation parameters on the syngas. It can be found that the ash content of microalgal torrefied pellet is much higher than that of most woody biomass. Although ash compositions can act as catalysts to enhance the gasification reaction, the extreme higher amount of ash in the microalgal torrefied pellet may cause sintering and agglomeration during gasification.

From the above co-gasification experiments, the results show that CO and CO₂ contents increase with increasing the ER, and CH₄ and H₂ show the contrary tendency. Injecting steam increases H₂ and CO₂ yields, but decreases CH₄ and CO yields, and LHV. A small amount of ash mixed with steam may reduce tar content. Therefore, the high-content ash in microalgal torrefied pellet affects the gasification products. It can be concluded that adding the proper amount of microalgal torrefied pellet can enhance CO yield and LHV without injecting steam.

From the study, we also can find that the high-content ash in the microalgal torrefied pellet dominates the gasification products, and the results show the contrary tendency, compared with gasification of woody biomass. However, to expand the utilization of microalgae as solid biomass fuels, more investigations may need to conduct to understand the role of the high-content ash in microalgae during gasification in the near future.

Acknowledgement

Financial support of this work by Taiwan Power Research Institute is gratefully acknowledged.

References

- [1] Bureau of Energy, MOEA. Energy Statistics Handbook 2011. Taipei, Taiwan: Bureau of Energy; 2012.
- [2] Gil J, Aznar MP, Caballero MA, Francés E, Corella J. Biomass gasification in fluidized bed at pilot scale with steam-oxygen mixtures: product distribution for very different operating conditions. *Energy Fuels* 1997;11:1109–18.
- [3] Long III HA, Wang T. Case studies for biomass/coal co-gasification in IGCC applications. In: *Proceedings of ASME Turbo Expo*; 2011 Jun 6–10, Vancouver, Canada; 2011. p. 1–15.
- [4] Van der Drift A, Van Doorna J, Vermeulenb Doorna JW. Ten residual biomass fuels for circulating fluidized-bed gasification. *Biomass Bioenergy* 2001;20:45–56.
- [5] Pan YG, Velo E, Roca X, Manyà JJ, Puigjaner L. Fluidized-bed co-gasification of residual biomass/poor coal blends for fuel gas production. *Fuel* 2000;79:1317–26.
- [6] Kumabe K, Hanaoka T, Fujimoto S, Minowa T, Sakanishi K. Co-gasification of woody biomass and coal with air and steam. *Fuel* 2007;86:684–9.
- [7] Mastellone ML, Zaccariello L, Arena U. Co-gasification of coal, plastic waste and wood in a bubbling fluidized bed reactor. *Fuel* 2010;89:2991–3000.

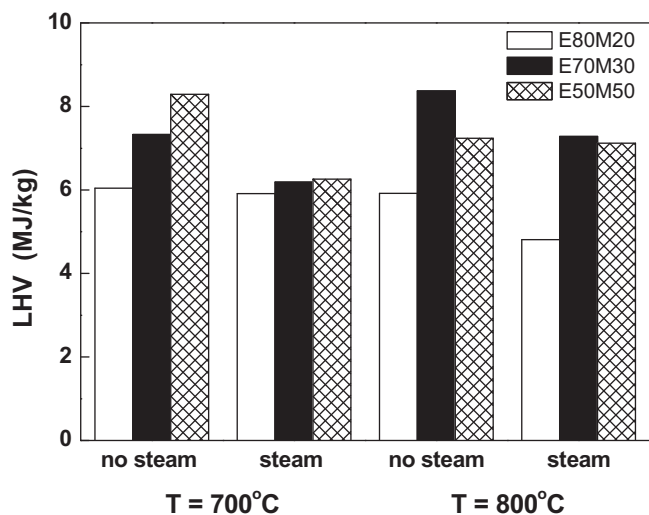


Fig. 10. Effect of steam injection on syngas LHV (ER = 0.3).

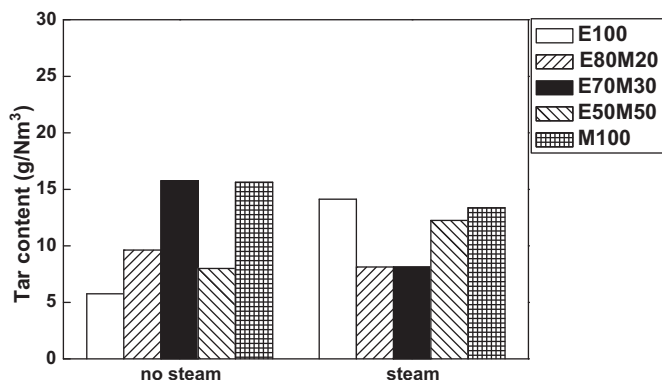


Fig. 11. Effect of steam injection on tar content from co-gasification (gasification temperature = 800 °C, ER = 0.3).

- [8] Phukan MM, Chutia RS, Konwar BK, Kataki R. Microalgae chlorella as a potential bio-energy feedstock. *Appl Energy* 2011;88:3307–12.
- [9] Wu KT, Tsai CJ, Chen CS, Chen HW. The characteristics of torrefied microalgae. *Appl Energy* 2012;100:52–7.
- [10] van Paasen SVB, Kiel JHA. Tar formation in a fluidised-bed gasifier. Petten, The Netherlands: ECN; 2004.
- [11] Lv P, Yuan Z, Ma L, Wu C, Chen Y, Zhu J. Hydrogen-rich gas production from biomass air and oxygen/steam gasification in downdraft gasifier. *Renew Energy* 2007;32:2173–85.
- [12] Narváez I, Orío A, Maria PA, Corella J. Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. *Ind Eng Chem Res* 1996;35:2100–20.
- [13] Qin K, Lin W, Jensen PA, Jensen AD. High-temperature entrained flow gasification of biomass. *Fuel* 2012;93:589–600.
- [14] Ahmed I, Gupta AK. Characteristics of cardboard and paper gasification with CO₂. *Appl Energy* 2009;86:2626–34.
- [15] Kantarelis E, Donaj P, Yang W, Zabaniotou A. Sustainable valorization of plastic wastes for energy with environmental safety via high-temperature pyrolysis (HTP) and high-temperature steam gasification (HTSG). *J Hazard Mater* 2009;167:675–84.
- [16] Weerachanchai P, Horio M, Tangsathitkulchai C. Effects of gasifying conditions and bed materials on fluidized bed steam gasification of wood biomass. *Bioresour Technol* 2009;100:1419–27.